AD-A146 073

University of Washington, Seattle, WA

Title: Thermal Model of Fire Suppression by Nitrogen Pressurization

Contract N00014-81-K-2034

Date: 22 Nov. 1983

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CONTENTS

1. INTRODUCTION

Fire suppression by nitrogen pressurization (FSNP) has been suggested as a fire protection method for pressurizable enclosures such as submarines. Engineering constraints restrict pressurization to levels only modestly beyond what is required for suppression in idealized laboratory experiments. Application of FSNP to operational enclosures, therefore, requires confident understanding of the effects of length-scale, and of realistic geometrical and thermal factors.

This project, funded through Office of Naval Research/ University of Washington Contract N00014-81-K-2034, has such understanding as its ultimate objective. The specific objective of this project is a mathematical model describing the effects of thermal factors supported by moderately small-scale experiments at the University of Washington and intermediate-scale experiments at the Naval Research Laboratory. Including two supported under a preceding contract*, six tasks comprise the project:

- I - Preliminary analysis and conceptual experimental design
- II - Detailed experimental design
- III - Construction and checkout of experimental system
- IV - Production operation of experimental system
- V - Theoretical model development
- VI - Application to Navy tests and design activities

* Tasks I and II, respectively, are described in reports submitted in December 1980 and February 1981 under Contract ONR N00014-75-C-0185.

Of the four Tasks included in this contract, only Task III was scheduled for completion in the first year of the project. The bulk of this Year End Report is devoted to that Task. Specifically, Section 2 describes the complete experimental system and its operating procedure as thus far evolved.

Task IV consists of definition of a matrix of production runs planned for the experimental system and subsequent systematic execution of these runs. The matrix was submitted to the Navy in May, 1982 and is recapitulated in Subsection 2.3 . Also in Subsection 2.3 is a complete set of reduced data for a single run to serve as an illustration and to indicate format. Completion of Task IV is not scheduled until the middle of the second year of the project. It is noted here that, by Year End, 19, and, by the present date, 75, of the planned matrix of 250 runs were completed. Beyond this and the above-indicated information in Subsection 2.3, Task IV is not dealt with in this report.

Task V is not scheduled for completion until even later in the second year of the project than Task IV. Much of this task requires experimental results only now becoming available. An interim summary of Task V is given in Section 3 .

Task VI, in its entirety, is scheduled for the second year of the project and is not treated in this report.

2. EXPERIMENTAL SYSTEM

The experimental system is conveniently considered as the primary system and the instrumentation. By the "primary system" is meant the hardware which achieves and contains the phenomena of interest; i.e., a fire, various thermal influences thereon, and means of pressurization. The primary system and the instrumentation are described in Subsections 2.1 and 2.2, respectively.

Subsection 2.3 sets forth procedures for using the experimental system to accomplish project objectives. Important information of this type ranges from operational details of individual runs to the overall experimental plan.

2.1 Primary system

The primary system exists in a basic configuration and three others incorporating auxiliary equipment. The basic configuration, as shown in Figure 2.1, consists of elements: the fire chamber, the pressurant supply subsystem, and the burner. Additional configurations entail radiative heaters to enhance heat transfer to the burner and fire seat, an ambient gas heater to indepently vary temperature of the gases flowing into the fire seat region, and insulation to reduce heat loss to the fire chamber walls. Photographs of the experimental equipment appear in Figures 2.2 and 2.3 .

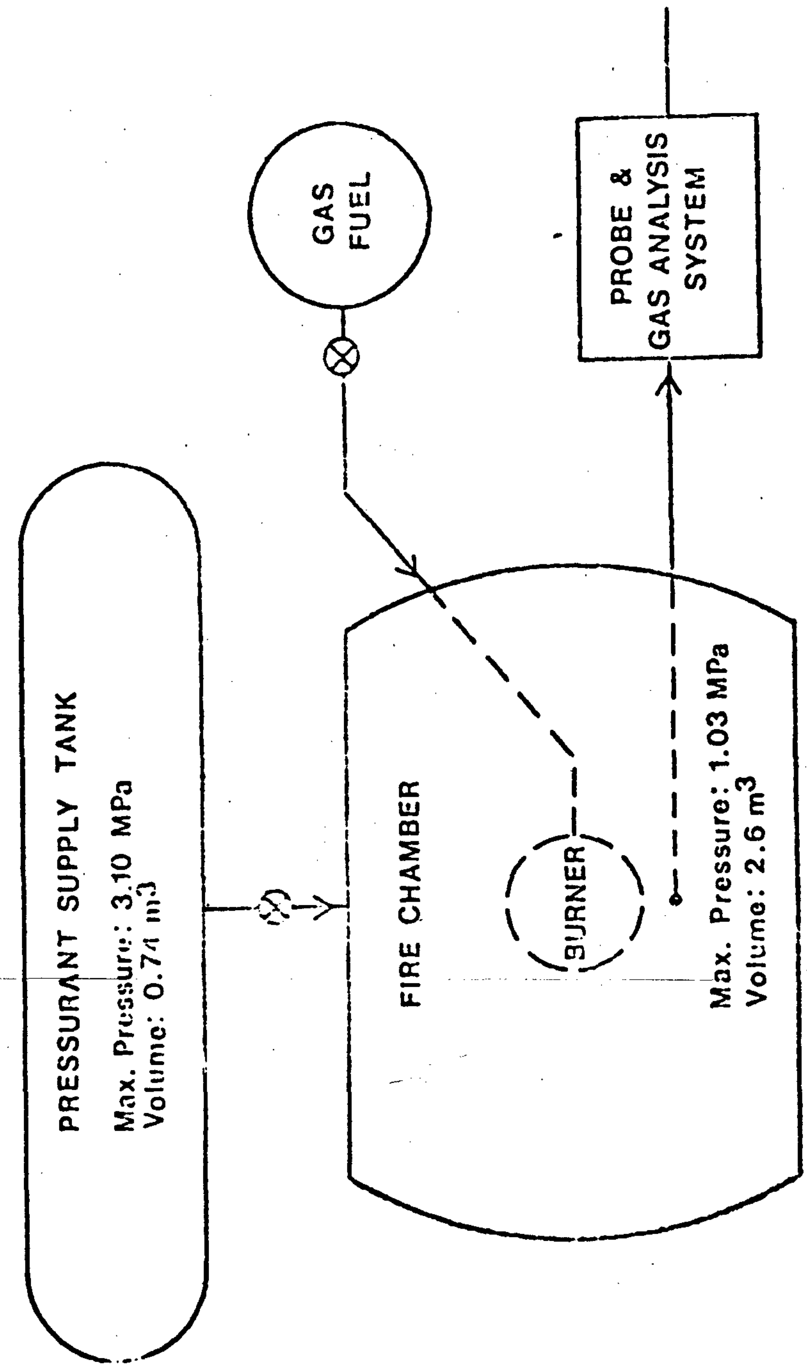


Fig. 2.1
BASIC SYSTEM CONFIGURATION

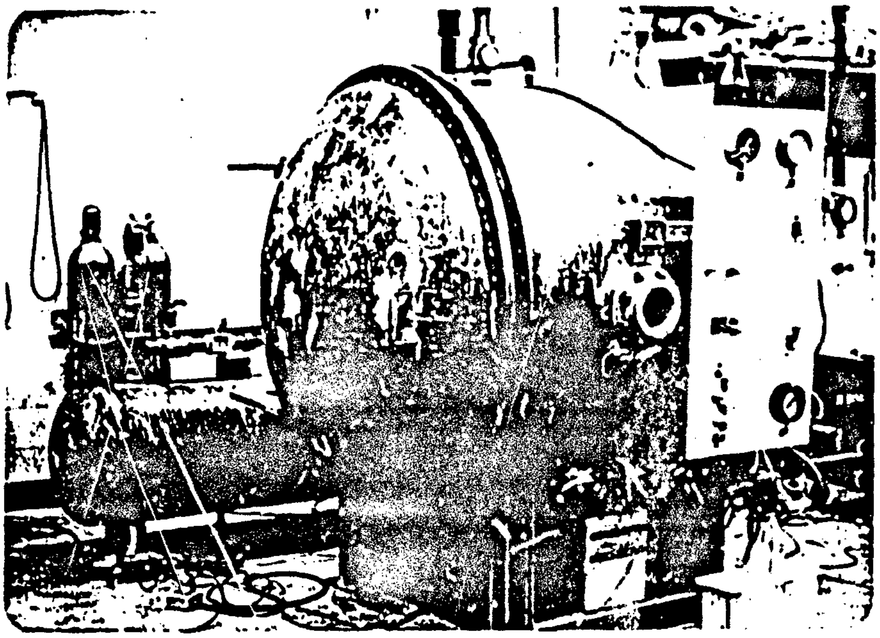


Figure 2.2   The Experimental Apparatus (front view)

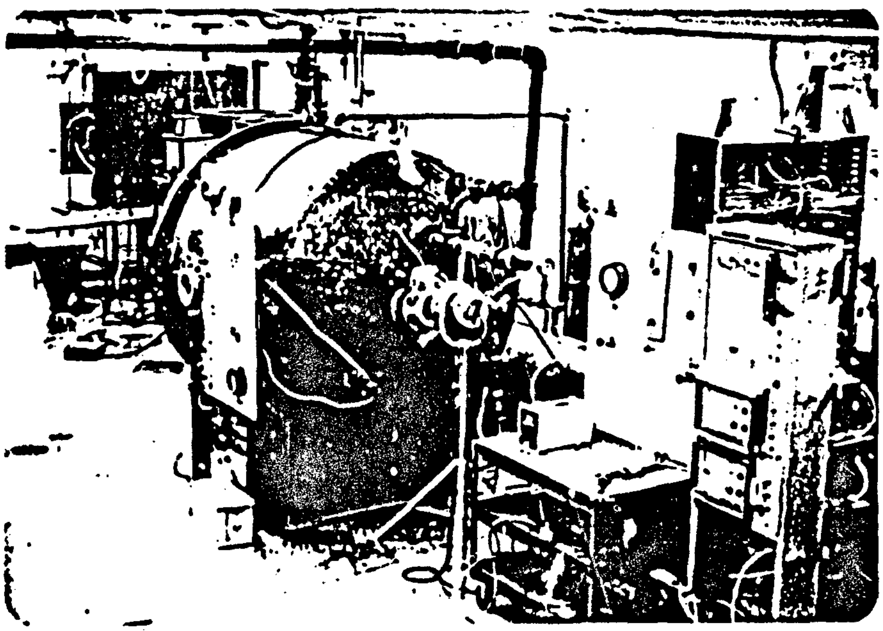


Figure 2.3   The Experimental Apparatus (rear view)

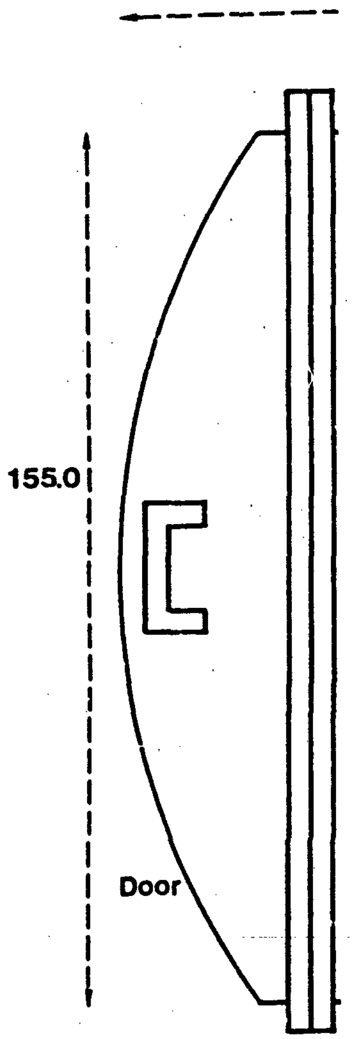
2.1.1 Fire chamber

Figure 2.4 is a drawing of the fire chamber. This is a 2.6 m3 (92 ft3) mild steel pressure vessel designed to code and constructed by Union Tank Works of Seattle. Rated working pressure is 1.03 MPa (150 psia) at temperatures to 260 oC (500 oF). Salient structural characteristics are:

Overall length	1.90 m (6.23 ft)
Outside diameter	1.55 m (5.08 ft)
Shell wall thickness	1.2 cm (0.50 in)
Cylindrical shell sidewall length ...	1.21 m (4.00 ft)
End caps	ASME flanged and dished heads
Head nuckle radius	6% cylinder dia
Head dish radius	85% cylinder dia
Minimum head wall thickness	1.1 cm (0.47 in)

A hinged door at the forward end provides full access to the fire chamber. The chamber also has three 10.1 cm (4 in) diam ports on the side and four 5.1 cm (2 in) diam ports on the aft end (opposite the hinged door). These ports are used, or available, for feedthroughs for electric power, fuel, cooling water, or instrumentation. On the top of the fire chamber are two (redundant) pressure relief valves (Lonergan Model 11W204) attached via 5.1 cm (2 in) diameter threaded connections. An additional 2.5 cm (1 in) threaded connetion on top is used for pressurant inlet.

In its basic configuration, the fire chamber walls are bare and the interior is empty except for a deck which supports the burner and instrumentation.


155.0
Door

The deck is a 124.5 cm long by 61.0 cm wide (49 by 24 in) lattice of 7.6 by 3.8 cm (3 by 1.5 in) steel channel covered by 20 gage expanded metal(1 x 1/2 in mesh). Figure 2.5 is a photograph of the fire chamber in the basic configuration.

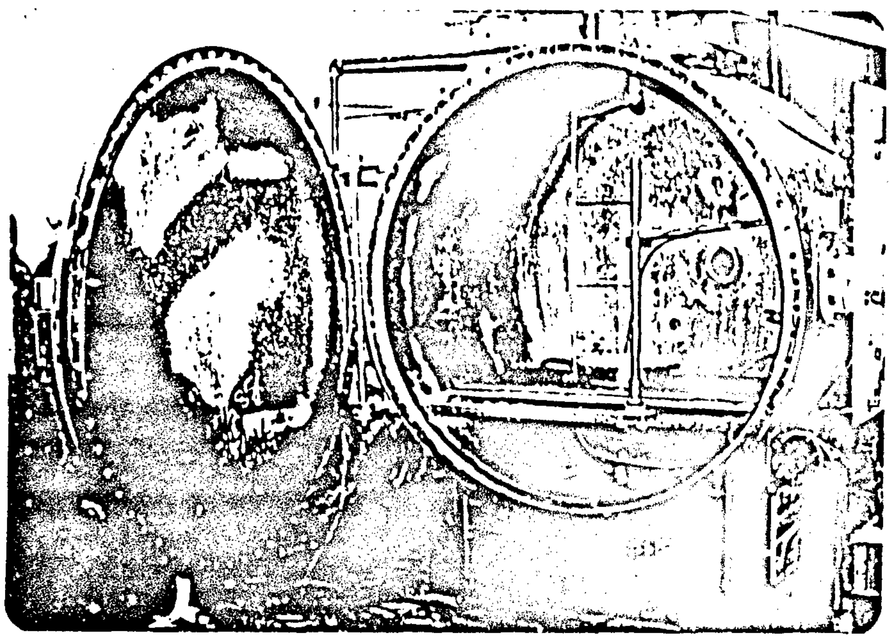


Figure 2.5 Interior of the Fire Chamber

2.1.2 Pressurant supply system

The pressurant supply system is shown in Figure 2.6 . The pressurant (99.8 % pure, commercial grade nitrogen) is received in bottles at approximately 15 MPa (2200 psi). The pressurant storage tank is pressurized as necessary from these bottles. This was also manufactured by Union Tank Works of Seattle. Its salient characteristics are:

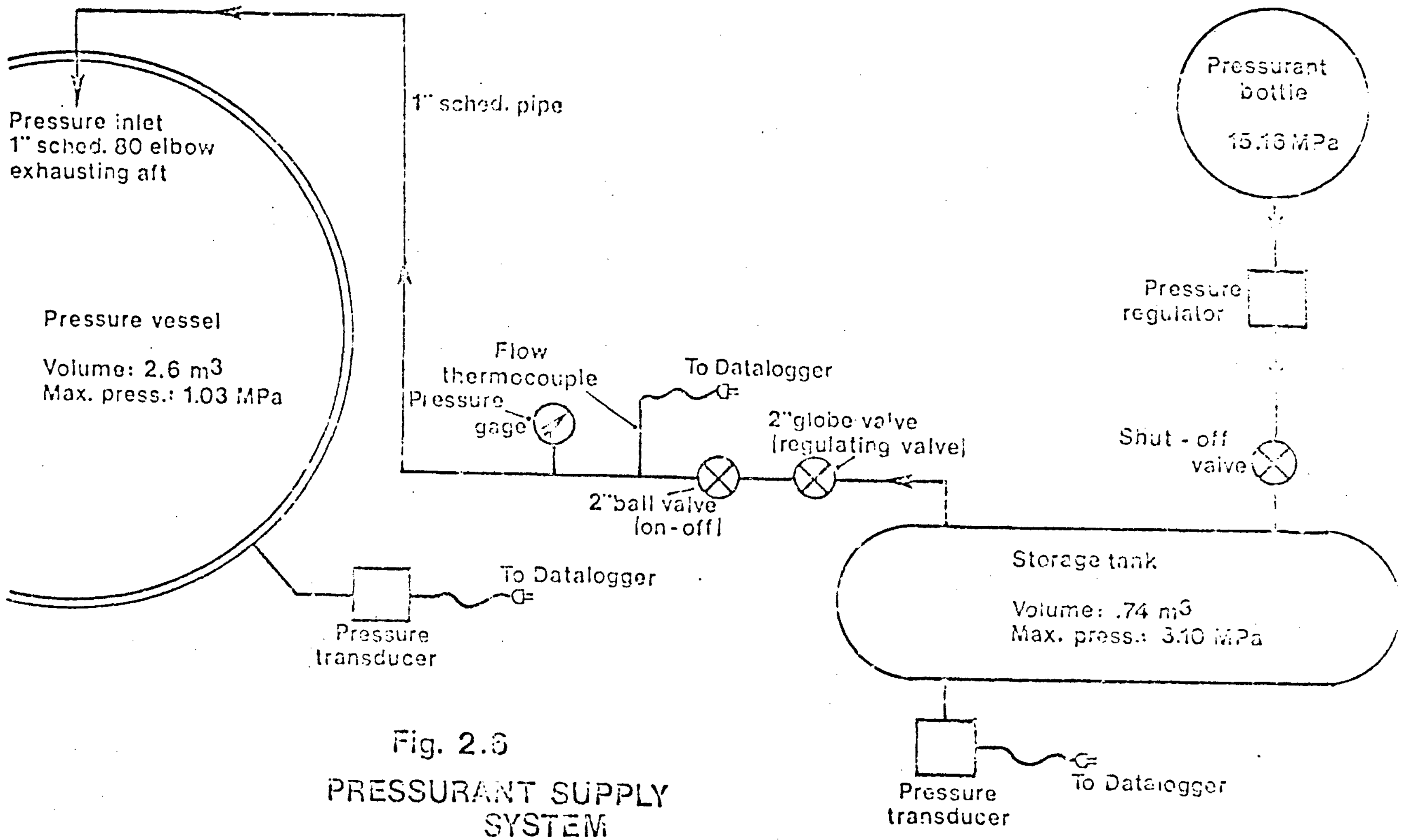


Fig. 2.6

PRESSURANT SUPPLY SYSTEM

Overall length .... 2.90 m (9.5 ft)

Outside diameter .... 0.61 m (2.0 ft)

Shell wall thickness .... 1.20 cm (0.50 in)

Volume .... 0.74 m^3 (26 ft^3)

Working pressure .... 1.03 MPa (150 psi)

From the pressurant storage tank is a nominal 5 cm (2 in schedule 80) line containing a Hammonds model 444 globe valve (for metering), a Worchester model 4117 ball valve (for quick flow start and stop), a thermocouple (ANSI type E, 20 gage wire), and a pressure gage. The line then reduces to nominal 2.5 cm (1 in schedule 80) line which passes up and into the fire chamber. Inside the fire chamber the flow is turned aft through a nominal 2.5 cm (1 in schedule 80) elbow and released.

2.1.3 Burner systems

There are two burner systems, one for fuels supplied to the fire chamber as gas (or vapor), and one for a liquid fuel burning as a pool in the chamber. The key feature of a pool burner is realistic coupling between energy feedback and burning rate. In order to assure such coupling in a desired burning rate regime, it is necessary to either augment the energy feedback or to Apartially compensate it by cooling or interference. A pool burner system was constructed but proved to need some re-design to achieve satisfactory performance. The pool burner system will be described in a separate report after satisfactory performance has been achieved.

The gas burner system consists of the burner itself, and gas supply and regulating equipment. Figure 2.7 shows the burner which, in essence, is a short cylindrical plenum topped by three layers of screen. The screen layers, together with the pre-distribution ring beneath provide a uniform flow of fuel across the entire burning area. The flange which holds the screen in place also defines the burning area. Presently, 25 cm (0.83 ft) and 30 cm (1 00 ft) flanges are in use. Figure 2.8 is a photograph of the gas burner with the 25 cm diam flange.

As shown in Figure 2.9, the gas supply system begins with pressurized bottled methane (93 % pure, commercial grade) or propane (95.5 % pure, commercial grade) regulated to a pressure hign enough to maintain critical (and, hence, constant rate) flow to the burner. (Because of the limited vapor pressure of propane, critical flow can be maintained only up to about 0.2 MPa (30 psia) initial fire chamber pressure.) Also included in the system are a flowmeter (Manostat 36-541-30), a metering needle valve (Hoke model no. 4RB236), and a toggle valve (Swagelok model no B1GS4) modified such that it must be held open by an operator in order for gas to flow. This toggle valve is a fail-safe mechanism to assure fuel shut-off in the event of an aborted run or ignition failure. Inside the fire chamber, the gas is split into pilot and main supply lines. During ignition, the pilot line alone is turned on and lit by the spark ignitor. Then the main supply is opened and, after overall burning is manifest, the pilot stream shut off. Finally the fuel flow rate is set to the level desired for the particular run at hand.

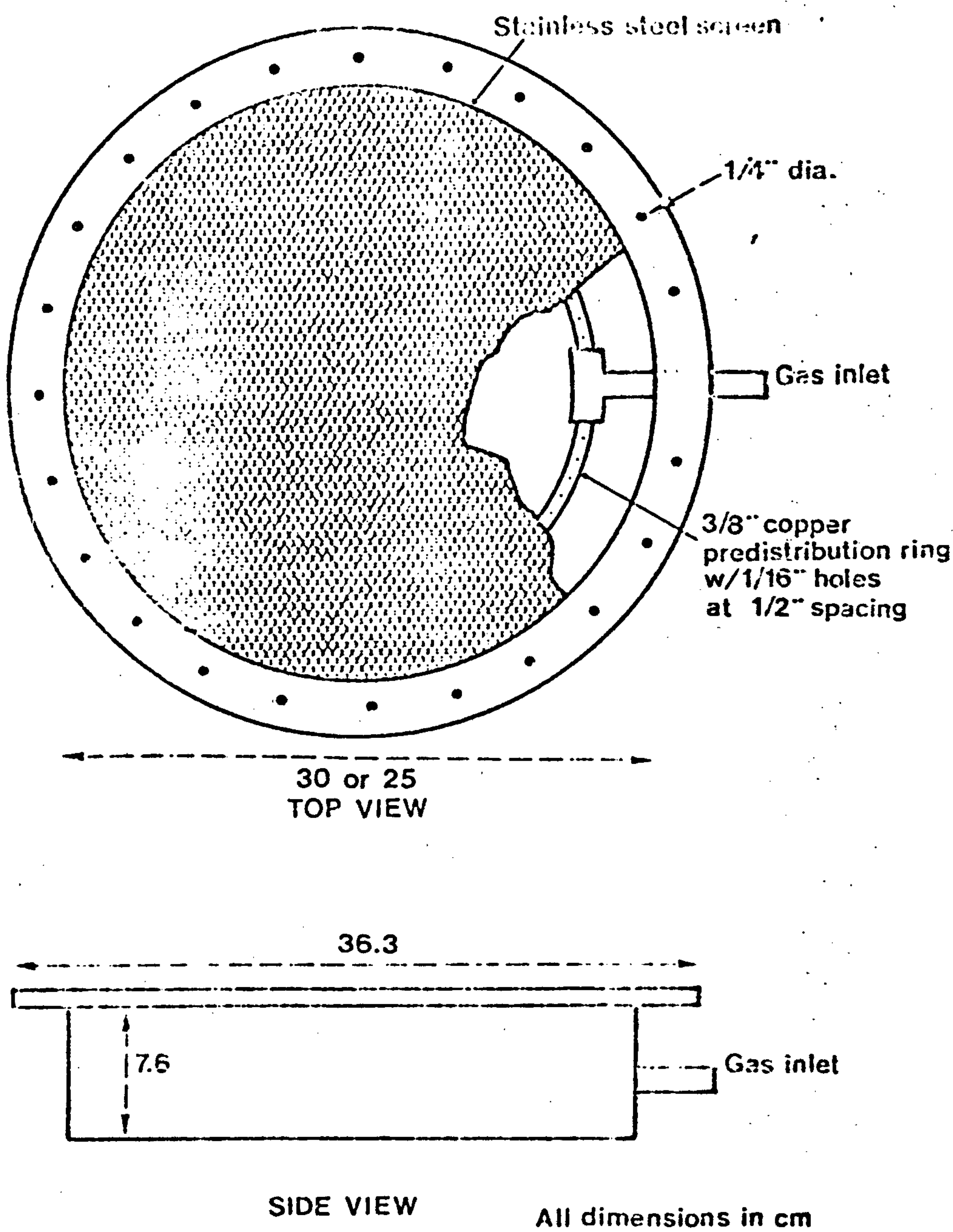


Fig. 2.7

GAS BURNER

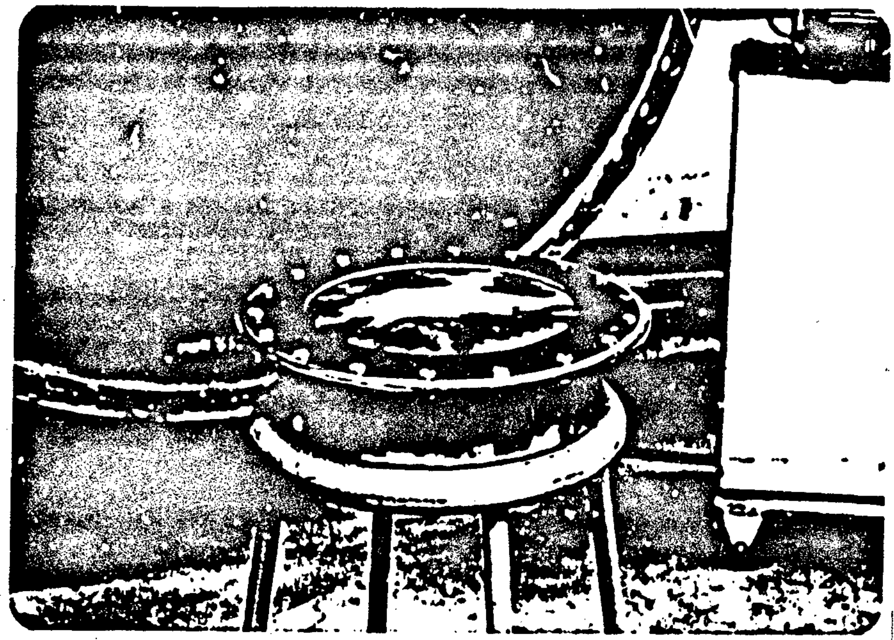


Figure 2.8 Gas Burner with 25 cm Flange

2.1.4 Special configurations

Special test configurations are those in which hardware is added to the primary system tr facilitate investigation of the independent effect of a par ticular thermal variable. The three special configurations are described below.

One special configuration incorporates radiant heaters to enhance radiation incident on the fire seat. Figure 2.10 shows a typical radiant heating unit wherein a 500 W quartz lamp (General Electric Model QH500T3) is mounted in an Al foil-lined steel reflector supported by a ring stand. Normally four of these units surround the burner as shown in Figure 2.11. Power is provided by a 30 Amp variac and monitored by wattmeter (Weston model no. 91C, full scale output - 2 kW). Tests have shown that less than 10 % of the lamp power is incident on the top of the burner. However, a much higher

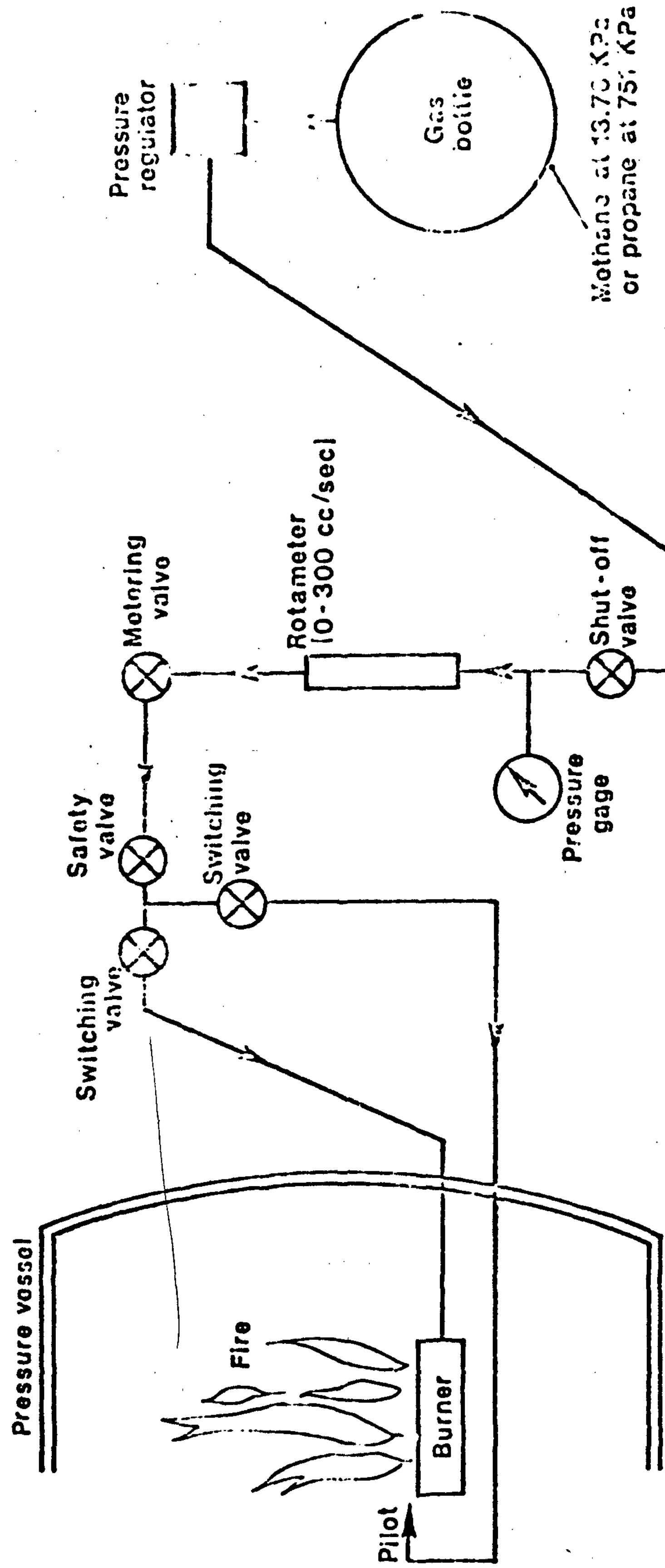


Fig. 2.9
FUEL GAS SUPPLY SYSTEM

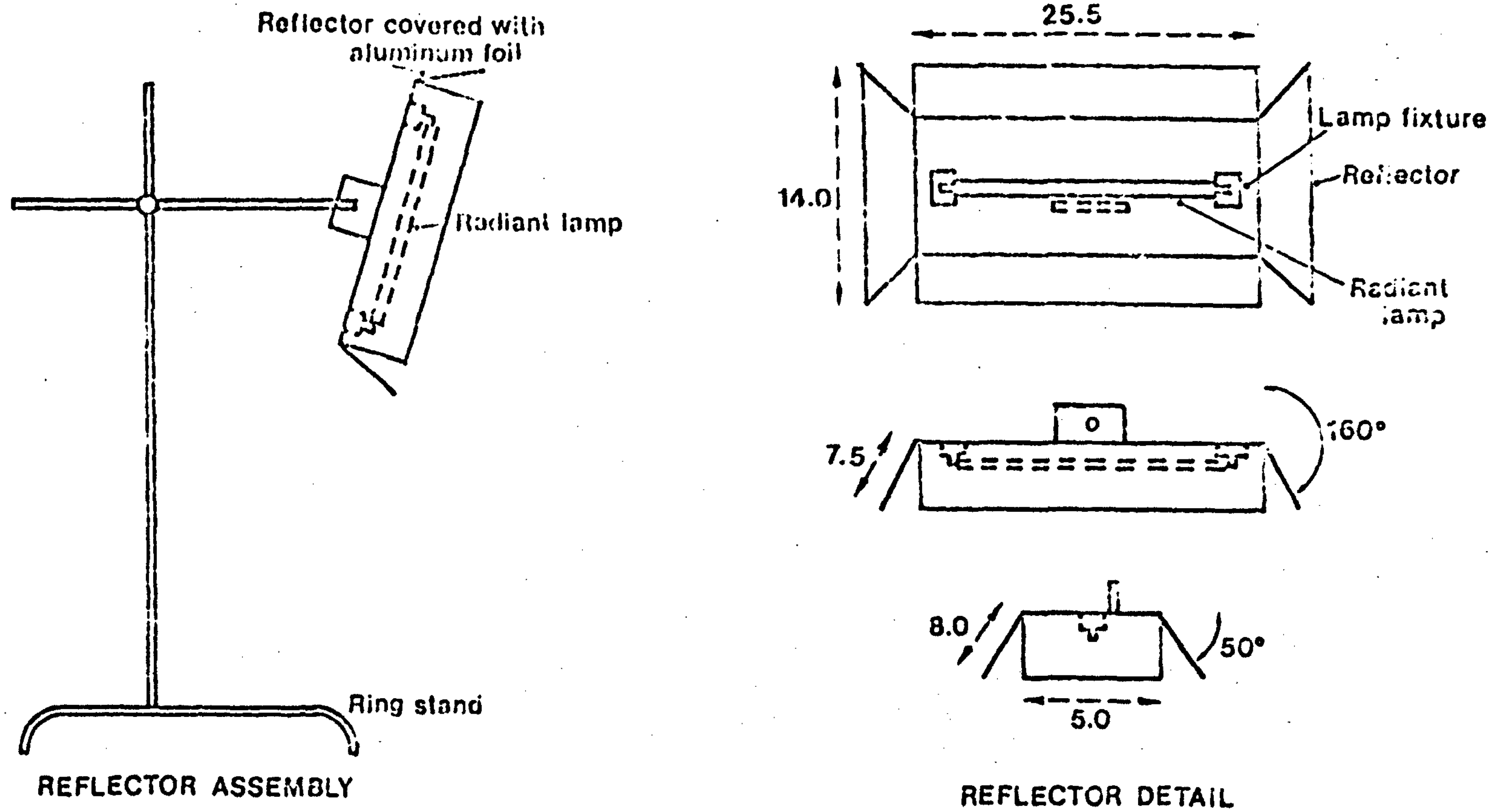


Fig. 2.10

RADIANT HEATER UNIT

All dimensions in cm

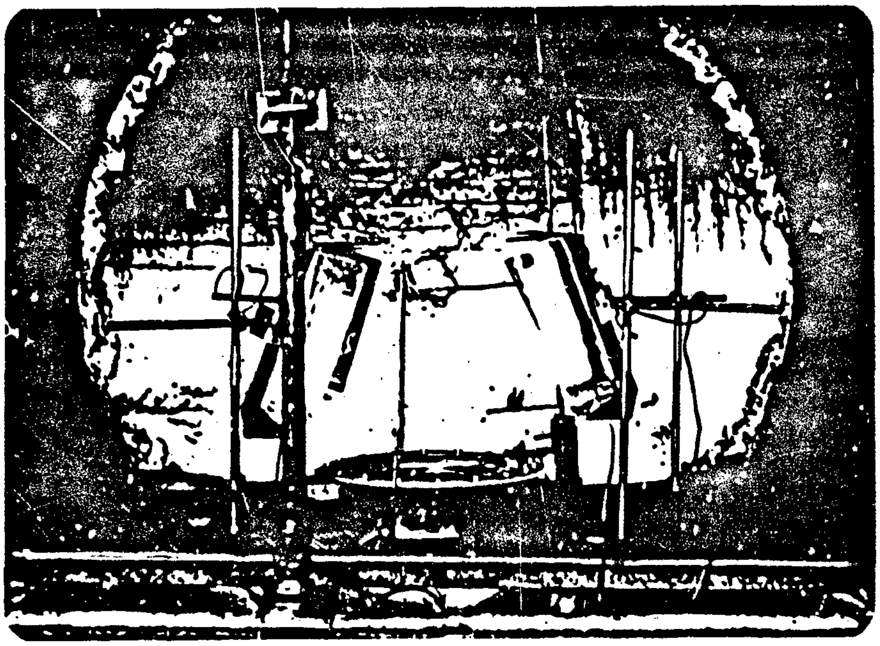


Figure 2.11 Interior of Fire Chamber with Radiant Heaters Installed

fraction would be expected to intercept the fire seat flame gases.

Figure 2.12 shows the ambient gas heater. The purpose of this unit is to raise the temperature of the air and other gases ingested into the fire seat. The annular unit surrounds the fire seat. Air from beneath the unit is driven through by a small blower. Heat is provided by a 1000 W coiled nichrome wire resistance element. The blower and heater can be adjusted to give a substantial range of flow rate and temperature differentials. Temperature is measured by interior thermocouple (ANSI Type T, copper-constantan, 20 gage wire). Figure 2.13 is a photograph of the main element of the ambient gas pre-heater. It is remarked that the height of ambient gas heater, relative to the burner is adjustable.

Scaling considerations suggest that convective heat losses will generally be larger relative to fire heat release rate or to pressurization energy in the

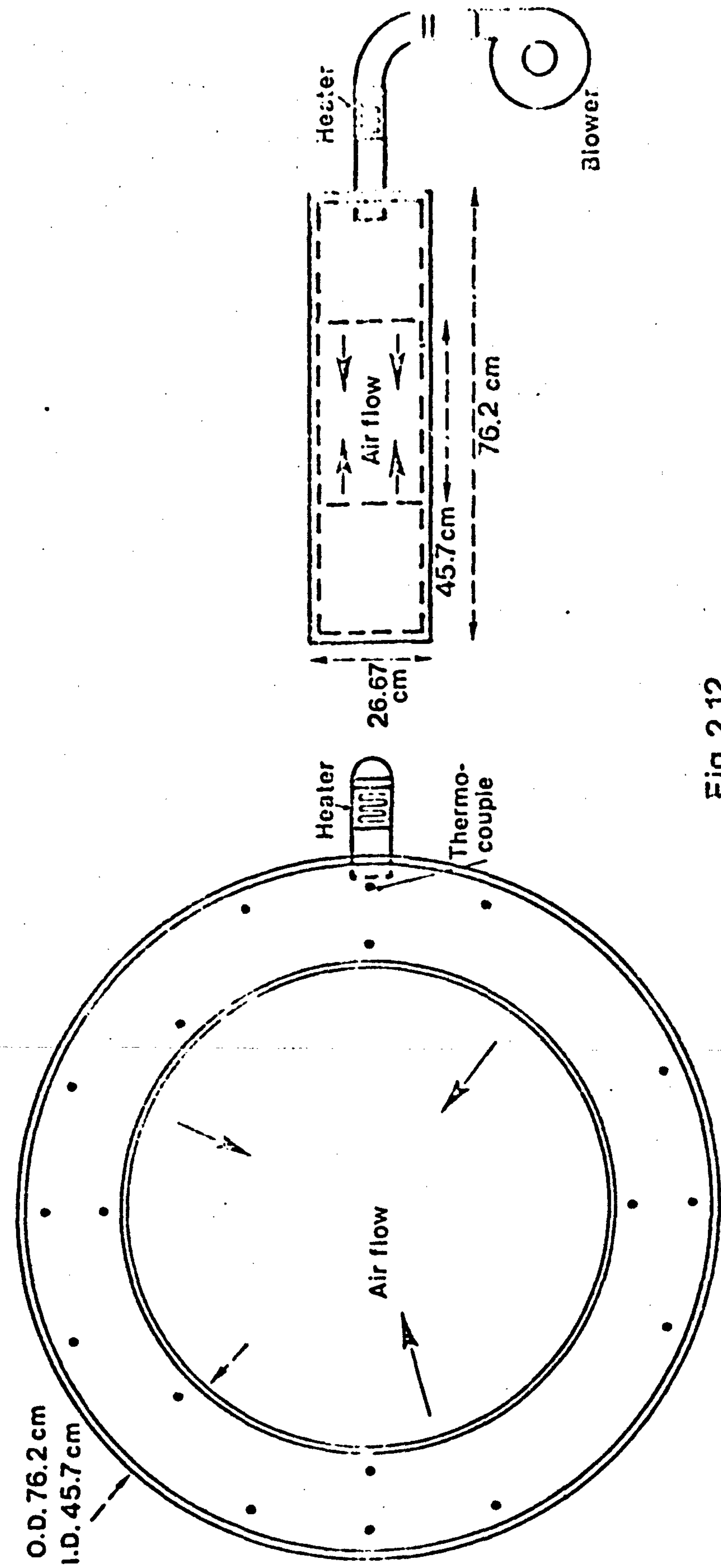


Fig 2.12
AMBIENT GAS HEATER

Figure 2.13 Ambient Gas Pre-Heater (main element)

University of Washington fire chamber than in larger enclosures such as the Naval Research Laboratory's Fire I or a prototype vessel. To compensate for such losses and, in general, to study the effect of convective loss magnitudes, insulation blankets have been provided. Figure 2.14 shows a photograph of the insulation as installed. The insulation (Johns-Manville Cerawool Blanket, 6 PCF density, 2.5 cm [1 in] thick) is supported by a steel lattice covered by expanded metal (20 gage, 1 x 1/2 in mesh). It is attached to the steel frame with wires punched through the blanket and twisted onto the expanded metal. The blankets can readily be installed in the fire chamber or removed from it. No atachments to the chamber interior are necessary. The photograph shows some soot discoloration; however, there is no evidence that the fire environment has in any way altered insulation performance.

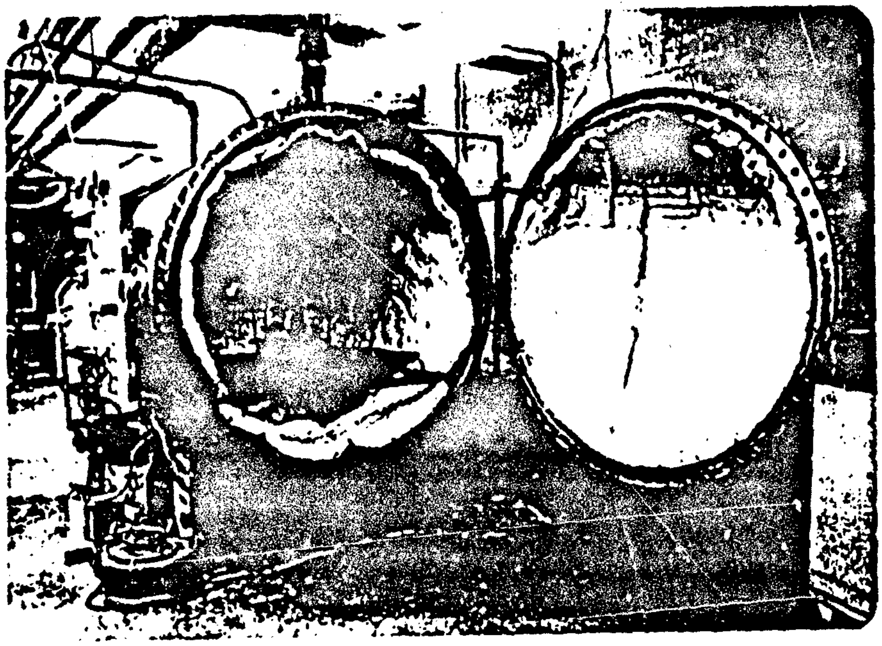


Figure 2.14 Interior of Fire Chamber with Insulation Installed

2.2 Instrumentation

In addition to photographs and hand-entered operating comments and visual observations, data collected in these experiments consists of gas composition, pressures, temperatures and event times. Except for photographs, all data is input to digital computer, appropriately processed, and stored on disc.

The desirability of video-recording, as well, is recognized but video-recording equipment is presently not available to the project.

2.2.1 Gas analysis system

A gas sample is drawn continuously from a prescribable point in the fire chamber, via a movable stainless steel probe, shown in Figure 2.15 . The probe is a 6.35 mm (0.25 in) tube with 0.89 mm (0.035 in) wall thickness. The probe inlet orifice is 2.0 mm in diameter. Configured in an "L" shape, the probe is movable through a full 46 cm diameter circle. It has 125 cm lateral travel. The probe is readily extendable to reach other points in the fire chamber; however, to date this has not been necessary. While the probe is easily movable from outside the chamber, its location is normally fixed during each individual run.

The gas sampling technique takes advantage of the fact that the fire chamber can be held at positive pressure at all times to maintain a continuous sample bleed to the atmosphere. Near the atmospheric outlet of the probe, a sample is drawn through on-line analyzers by vacuum pump (Metal Bellows Co.,

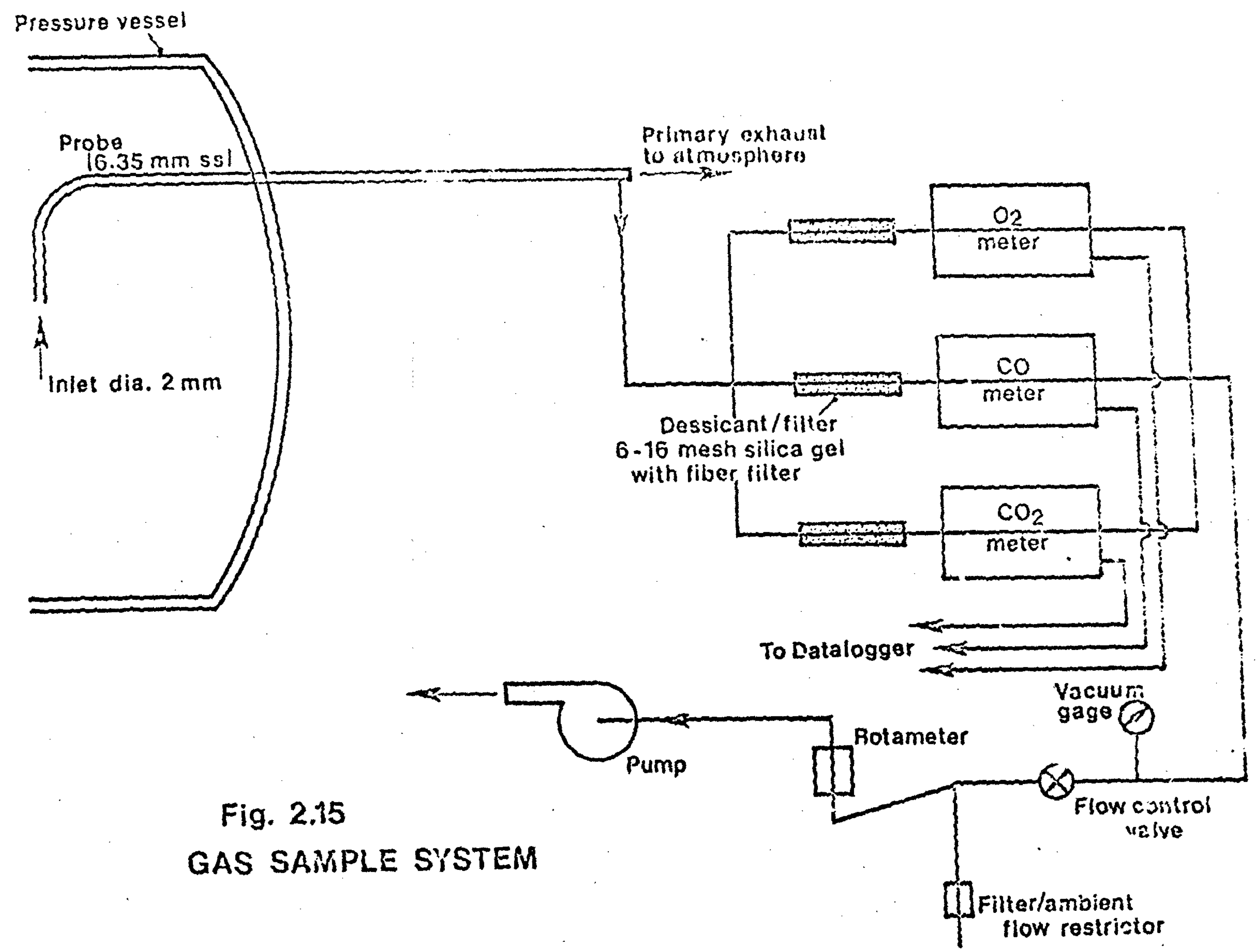


Fig. 2.15
GAS SAMPLE SYSTEM

Model MB-155). This arrangement assures constant sample flow rates through the analyzers.

Upstream of the analyzers is a silica gel dessicant (6-16 mesh) and a fiber filter assembly to remove particulates from the stream. The analyzers are as follows:

oxygen .... Taylor Instrument, Model 570A
carbon monoxide .... Beckman, Model 564 (NDIR)
carbon dioxide ..... Beckman, Model 564 (NDIR)

The total analyzer flow is monitored by vacuum gage and rotometer (F&P, Model 2-F 1/4-20-20-5/30).

2.2.2 Pressure measurement

Pressures are recorded from strain gage type transducers in the fire chamber (Statham Model PA822-100, range 0-100 psia) and the pressurant suply tank (Teledyne Model 206-3A, range 0-1000 psia). The accuracy of each transducer is 0.25% full scale. Additionally, several bourdon gages are mounted for visual monitoring by the operators.

2.2.3 Temperature measurement

An array (presently 10, as shown in Figure 2.16) of thermocouples is installed in the fire chamber. All thermocouples are AWG 24 (0.51 mm wire diam), ANSI Type T (copper-constantan). The complete set of ANSI Type T

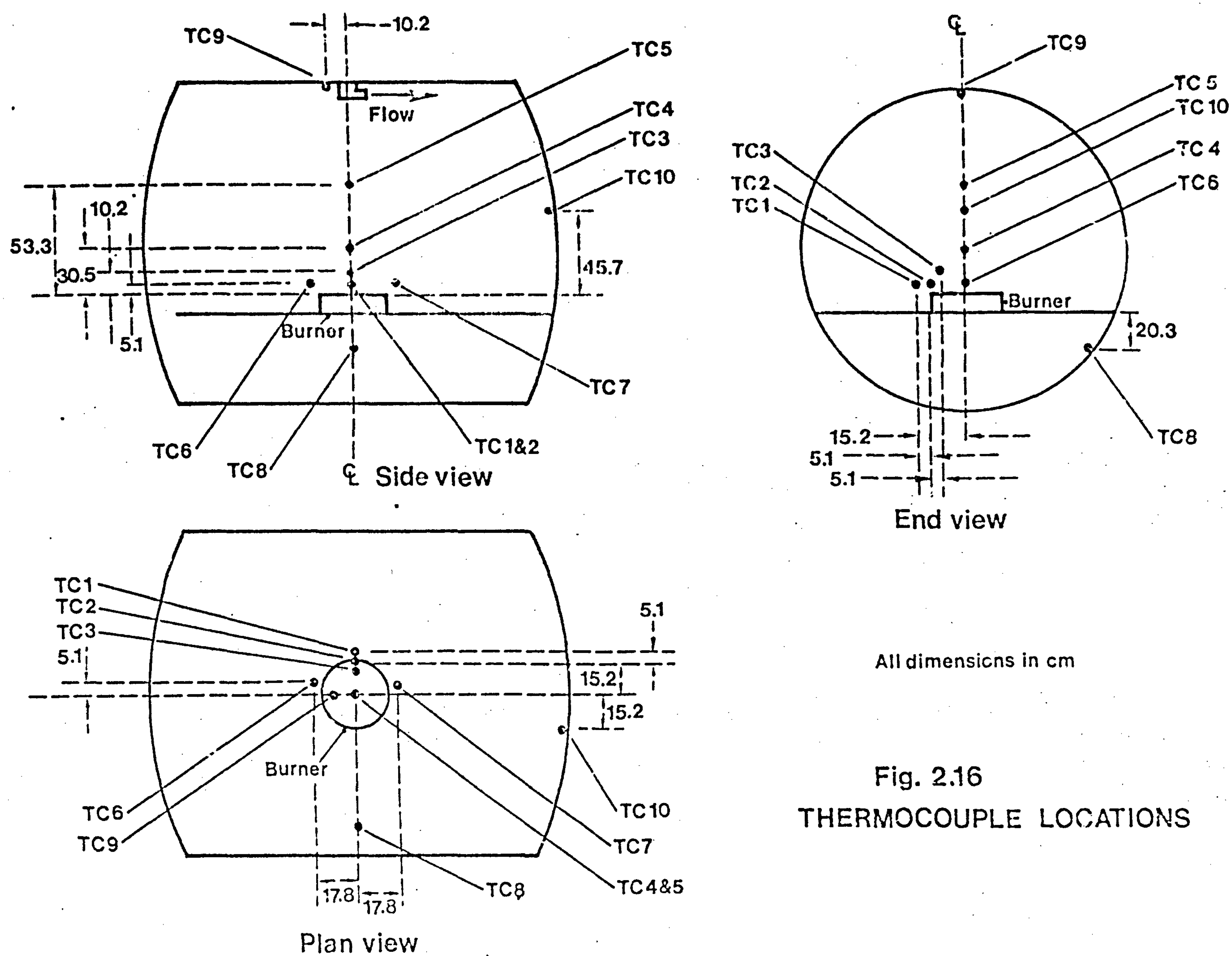


Fig. 2.16
THERMOCOUPLE LOCATIONS

wire pairs passes through the chamber wall embedded in Ductorseal epoxy feed-throughs.

Thermocouples 1-7 are placed to provide data characterizing the fire seat vicinity and thermocouples 8-10 to provide a general indication of the fire chamber as a whole. Several of the thermocouples are close enough to the flames to warrant concern with possible output distortion to radiation. Worst case analysis indicates a maximum of 10% of the output due to radiation. Instead of the further complication of shielding, it was decided, for this project, to minimize radiation by choosing low view factor orientations, and to make analytical corrections in data analysis as needed.

2.2.4 Data collection and storage

Data collection is accomplished with a Fluke Model 2240B Datalogger and a Digital Equipment Corp. (DEC) PDP11-44 computer. The datalogger samples all of the 20 quasi-continuous channels (11 thermocouples, 3 composition analyzer outputs, 2 pressure transducer outputs, and 4 time signals) at pre-set intervals (normally 2 seconds) and transmits this data to the computer for disc storage. With present equipment, any significant increase of sample rate would necessitate corresponding elimination of some channels.

The datalogger converts thermocouple signals to temperatures before transmission to the computer. All other signals are digitized by the datalogger but processed otherwise by the computer.

The time signals correspond to 4 significant events: main burner ignition,

pressurant flow initiation, extinction, and cessation of pressurant flow. Via manual input, each time signal channel voltage acquires a step voltage at appropriate event times.

Complete single run data reports (excepting photographs, of course) can be produced within a few minutes of completion of a run. An example is presented in the Appendix.

2.3 Experimental methods and procedures

A matrix of runs planned to accomplish the objectives of the project was submitted separately in June, 1982. Included in this matrix are two types of variables. Operationally these are classed as "general" and "special" variables. General variables include fuel type, burner size and location, burning rate (or equivalent parameters), initial pressure, and pressurant injection characteristics. Special variables include those dependent on auxiliary interior equipment or on a non-standard initial chamber atmosphere. Corresponding methods and procedures are covered in the following two Subsections.

2.3.1 General operations

The more important preliminary steps are arrangment of the fire chamber interior for the experiment sequence of interest, provision of fuel and pressurant supply (pressurant supply tank at 2.41 MPa at the start of each run), hooking up the datalogger and properly interfacing it the computer, and calibration of analyzers.

Since the liquid fuel burner system is not yet operational, ignition and fuel flow procedures, for gaseous fuels only, are described here.

Initially, the fire chamber is pressurized with shop air up to 3 atm, as specified. The datalogger/computer combination is placed in operation for 10-20 seconds before ignition. The ignition sequence consists of actuation of the spark ignitor, turn-on of pilot propane, turn-off of spark ignitor after pilot is lit, turn-on of main burner fuel at specified rate, and turn-off of pilot fuel once main burner is lit. This sequence can take as much as 10 seconds.

The main burner is allowed to burn for 30 - 40 seconds, to stabilize, and as much longer as specified. Then the ball valve on the pressurant supply line is opened a specified number of turns. Pressurant flow is cut off aftrr the flame is visibly extinguished.

After cessation of pressurant supply, data recording continues until the sample composition (as indicated by analyzers) is thoroughly stable; typically, this takes from 3 - 5 minutes.

The fire chamber is then purged with shop air, and another run carried out, in replication or with new parameters. As many as 11 runs have been carried out in the course of a single session with a fixed fire chamber setup.

2.3.2 Special variables

Enhanced thermal radiation on the burner surface and fire seat flames is

provided by auxiliary radiant heat lamps. Four lamp units provide maximum power of 1.7 kW . Because the mere presence of the lamps may disturb the fire seat flow field, power level will be varied from zero to 1.7 kW with the lamps physically in place.

Initial oxygen fraction is another variable of interest. It is convenient and safe, with the present system, vary oxygen fraction below the normal atmospheric value by adding nitrogen to the initial fire chamber atmosphere. Preliminary experiments have shown that pilot flame ignition can be easily accomplished with oxygen fraction down to 17.5% .

Heat losses to fire chamber walls can, plausibly, reduce the temperature of gases ingested into the fire seat. Such reduction, if important, should be most appreciable at relatively small length scales, such as in the experimental system described in this report. The insulation assembly described in Subsection 2.1.4 is intended to delineate the any effects of chamber wall heat losses. Because of the labor of installation, the insulation assembly will be left in (or out) of place for relatively large numbers of runs.

The fire seat ambient gas heater is another means of adjusting the temperature of gases ingested into the fire seat. The mere presence of this device (shown in Figures 2.12 and 2.13) very likely introduces a severe flow distortion. Therefore, it will be necessary to achieve a range of flow rates and temperature rises (including no temperature rise) with the device in place. Procedural details will be established as use of the ambient gas heater progresses.

3. THEORETICAL MODELLING

At this writing, a full theoretical model has not been formulated. In essence, the theoretical model will consist of a suitably concrete and refined version of the Damkohler criterion set forth by Williams (J. Fire & Flamm., 5,1, 1974, 54). The Damkohler criterion equates a characteristic chemical time t_c with a characteristic residence time t_r. The heart of the theoretical modelling task is derivation of explicit relations for t_r and t_c in terms of operational variables.

Undoubtedly, t_c is strongly temperature-dependent? What is the relevant temperature? In diffusion flames, the temperature in the vicinity of the stoichiometric surface is much higher than anywhere else. It has long been known that the temperature at the stoichiometric surface is (to the extent that certain approximations, e.g., infinite chemical rate and unity Lewis Number, are valid) the same as the adiabatic flame temperature T_s of a stoichiometric mixture of the fuel vapor and the "air" in which it burns diffusively. It is reasonable, in the system of interest here, that the relevant "air" is that mixture of fresh chamber gas and combustion products ingested into the fire seat.

Of course, in a region where extinction is controlled, the infinite chemical rate assumption cannot be valid and the tempperature will, in general, be less than T_s. However, the same factors which control Ts should exert some control over temperature in the extinction region and, hence, on t_c. Additionally, the temperature-dependence of the chemical rate must also play a role. This dependence can be characterized by an overall activation

energy E . Because E is roughly the same for a wide range of hydrocarbon fuels, it is likely that T_s is the dominant correlative variable for t_c .

What is the physical basis of rational establishment of t_r ? This question is still very much open. However, the relevant residence time would be that where the ultimate mixture ratio is near stoichiometric. One possible means of construction of t_r would combine a characteristic diffusivity D and a characteristic buoyant velocity V , i.e.

$$t_r = C\, D/V^2$$

where C is a coefficient derivable from boundary layer theory in laminar flames and adjustable in terms of a Grashof (or Rayleigh) Number in the turbulent case. In the laminar case, D varies inversely with pressure and more strongly with temperature. In the turbulent case D should vary slowly with Grashof Number and thus be incorporable in C . Quantity V should depend very modestly on temperature (through bouyancy) and as a characteristic burner dimension to the 1/2 power.

The details of all of the above suggested development have yet to be carried out. However, it would appear that t_r probably does not depend strongly on any variable of interest. In contrast, the chemical time t_c will probably be highly sensitive to the above-cited adiabatic flame temperature T_s . Accordingly, the first step is establishing a theoretical model is to test critically the hypothesis that there is a critical value of T_s . In doing so, experimental measurement of temperature and oxygen fraction in the fire seat vicinity can be used to compute T_s . This value can be further refined

by subsidiary analysis to account for radiative losses from (or additions to) the fire seat.

Of course, the precise definition of "fire seat" is not yet established, either. While it is not disputed that the fire seat, for open burners, lies within a burner diameter or so of the burner surface. The capability of experimentally selecting variable location for temperature and oxygen fraction in the fire seat vicinity should help deduce a concrete fire seat definition for purposes of FSNP.

APPENDIX

RUN SUMMARY

RUN NUMBER: 25

DATE: 8/23/82

TEST CONFIGURATION:
(See Configuration Record for Details)

Chamber Configuration-	3
Nitrogen Injection Configuration-	1
Instrumentation Configurations	
Thermocouples-	1
Pressure Transducers-	1
Gas Sampling and Analysis-	1

FIRE:

Fuel-	Propane
Burning Rate ([illegible])-	0.0134 m/s
Burner Diameter-	0.300 m

INITIAL CONDITIONS:

Pressure in Pressur. Vessel-	1.383	atm
Temperature in Pressure Vessel-	28.5	C
Oxygen Mole Fraction-	21.18	%
Pressurant Mole Fraction-	0.00	%
Carbon Dioxide Mole Fraction-	0.00	%
Carbon Monoxide Mole Fraction-	0.00	%

SUPPRESSION TECHNIQUE:

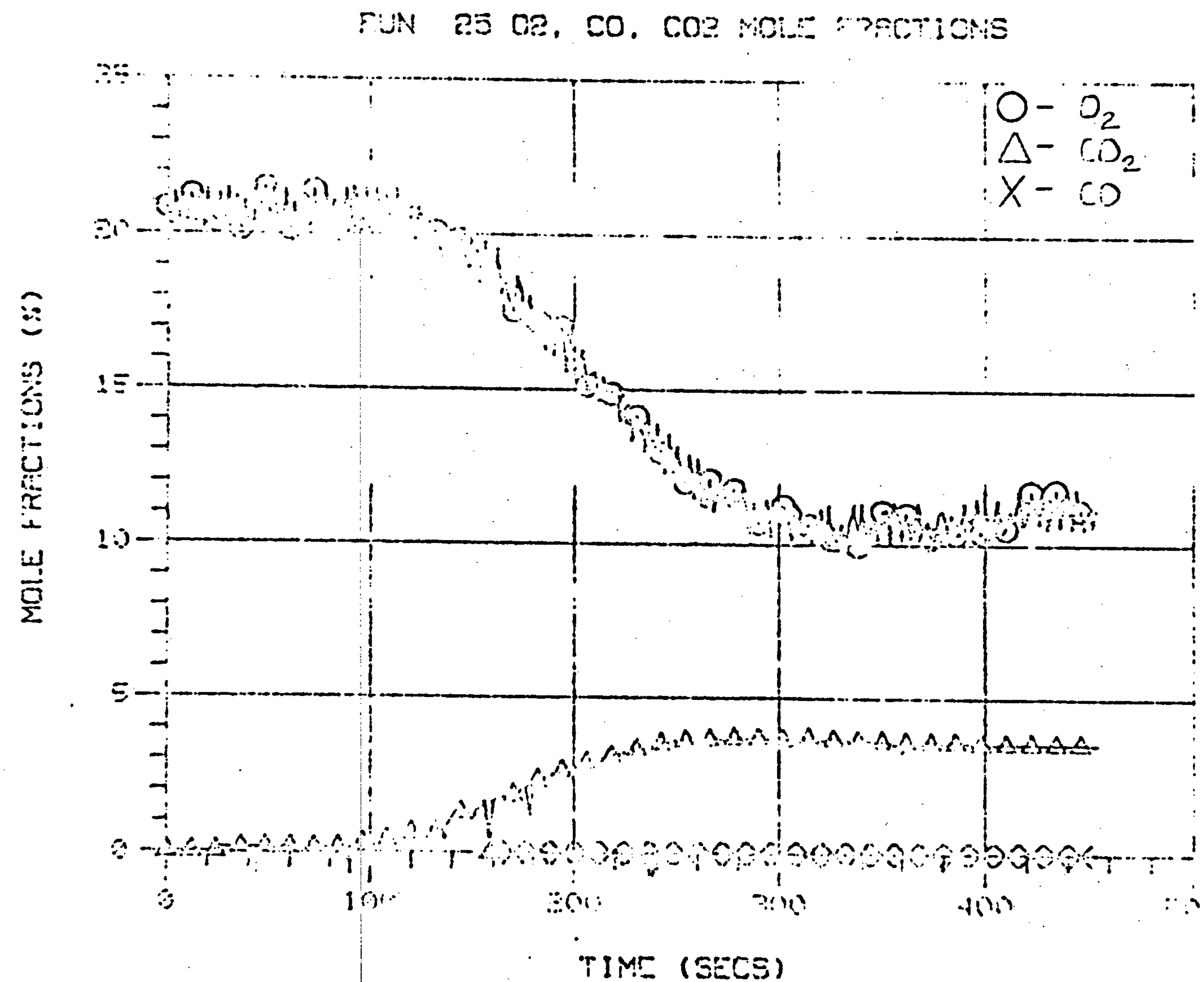
Elapse Time, Ignition to Start Suppression-	46	sec
Elapse Time, Start Suppression to Fire Out-	146	sec
Elapse Time, Fire Out to Nitrogen Off-	2	sec
Average Pressurant Addition Rate-	11.92	gms/sec

FINAL CONDITIONS:

Pressure In Pressure Vessel-	2.546	atm
Temperature In Pressure Vessel-	33.8	C
Oxygen Mole Fraction-	11.46	%
Pressurant Mole Fraction-	35.98	%
Carbon Dioxide Mole Fraction-	3.67	%
Carbon Monoxide Mole Fraction-	0.00	%

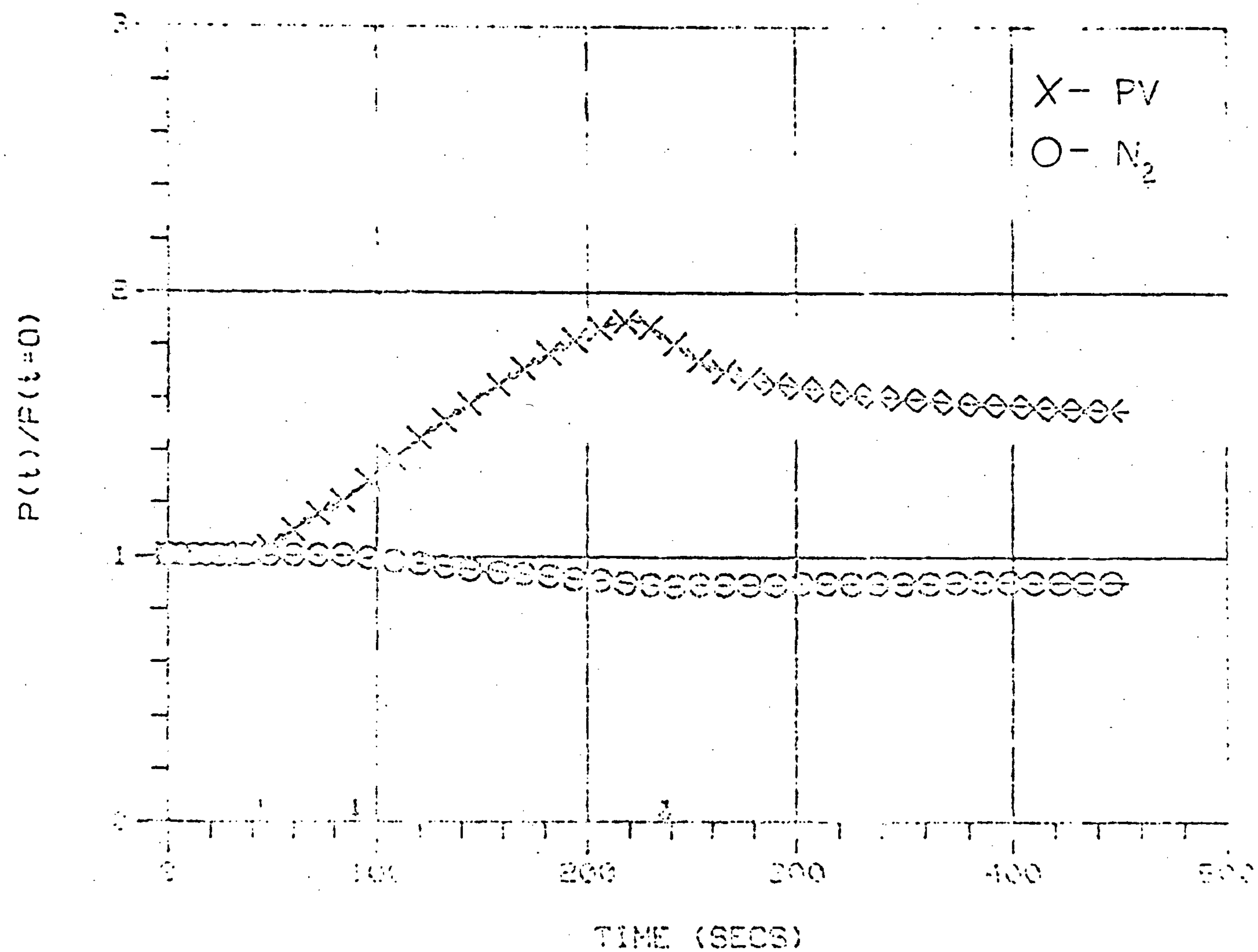
COMMENTS:

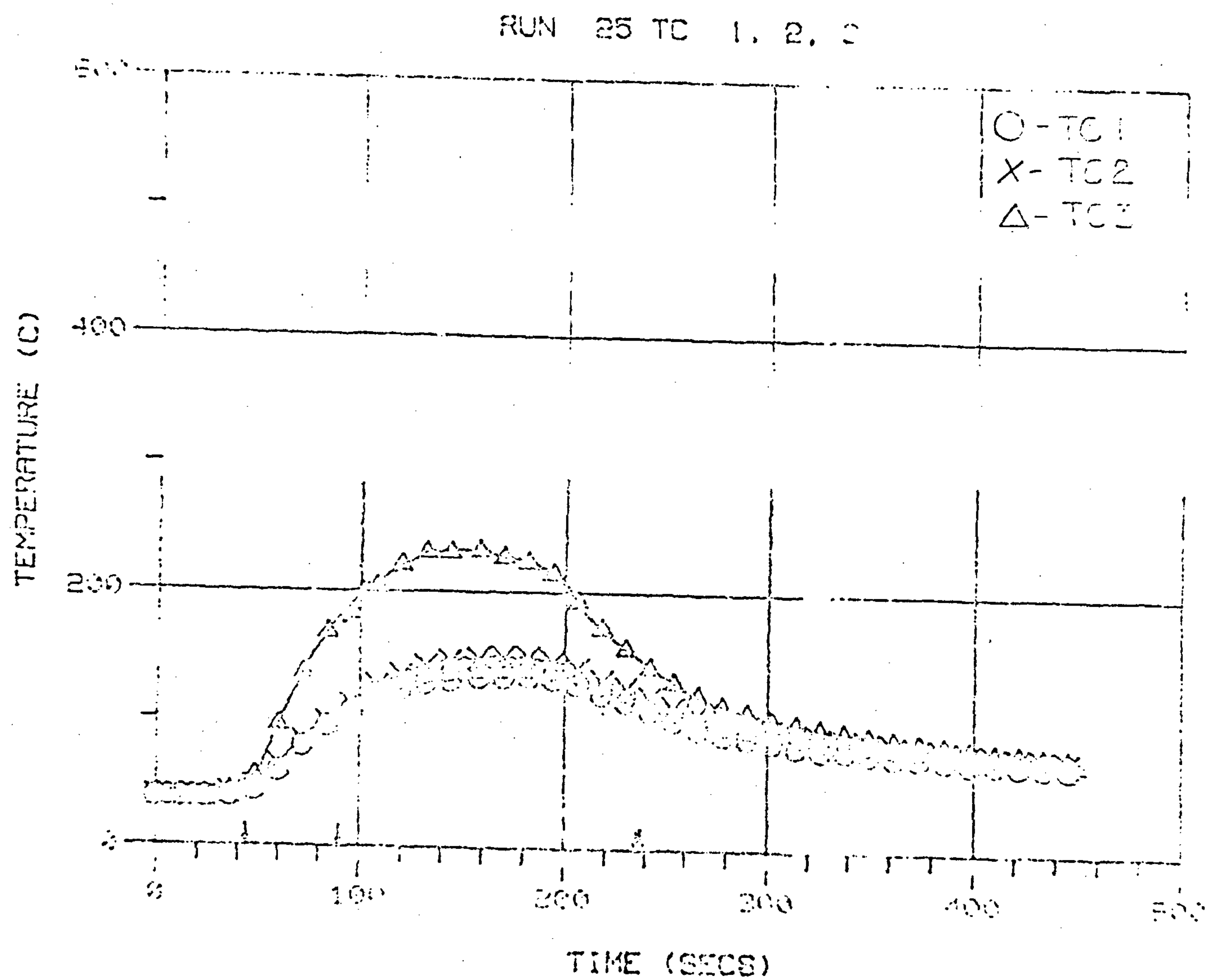
NONE



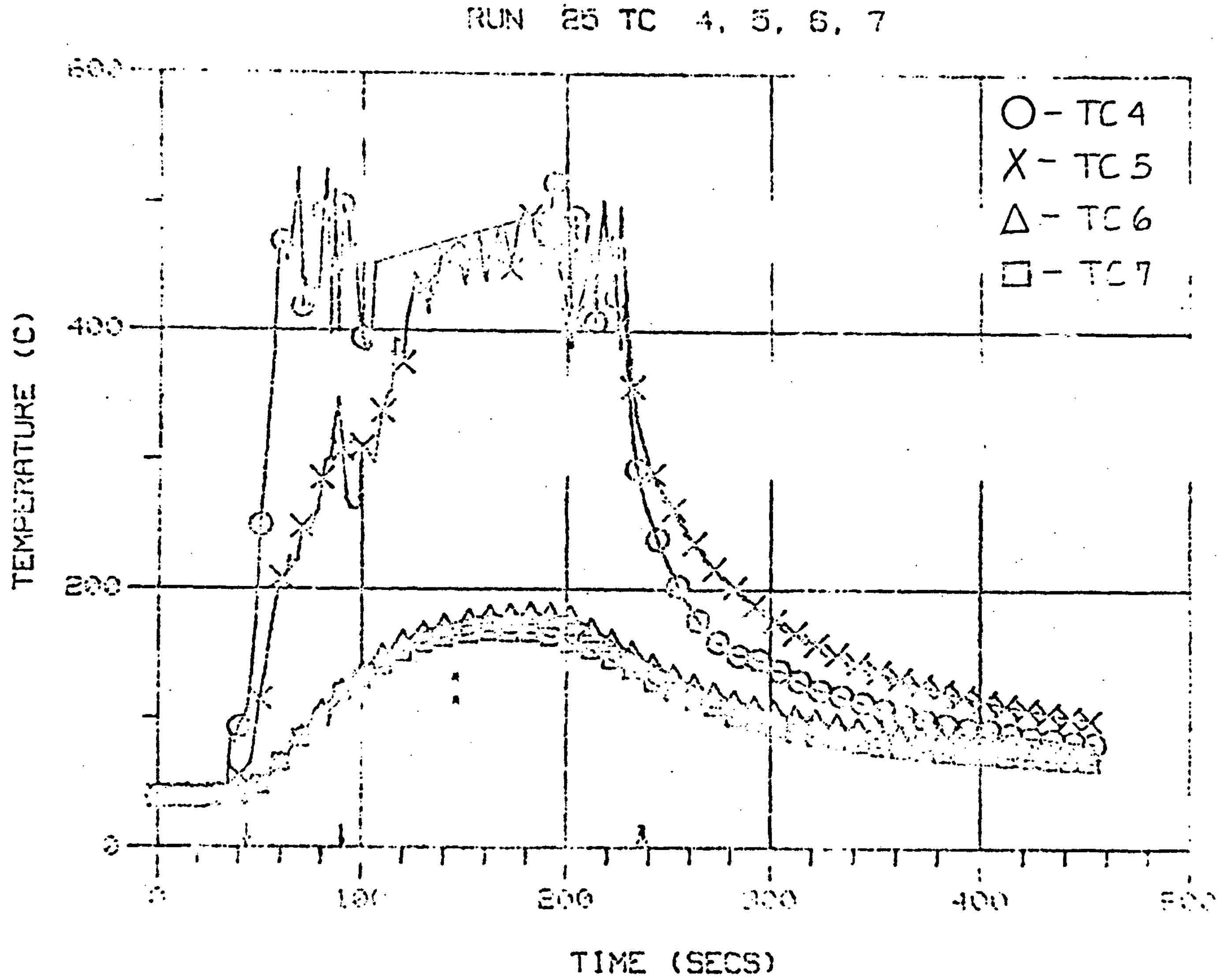
FUN 25 O2, CO, CO2 MOLE FRACTIONS
O - O_2
Δ - CO_2
X - CO
MOLE FRACTIONS (%)
25
20
15
10
5
0
0
100
200
300
400
TIME (SECS)

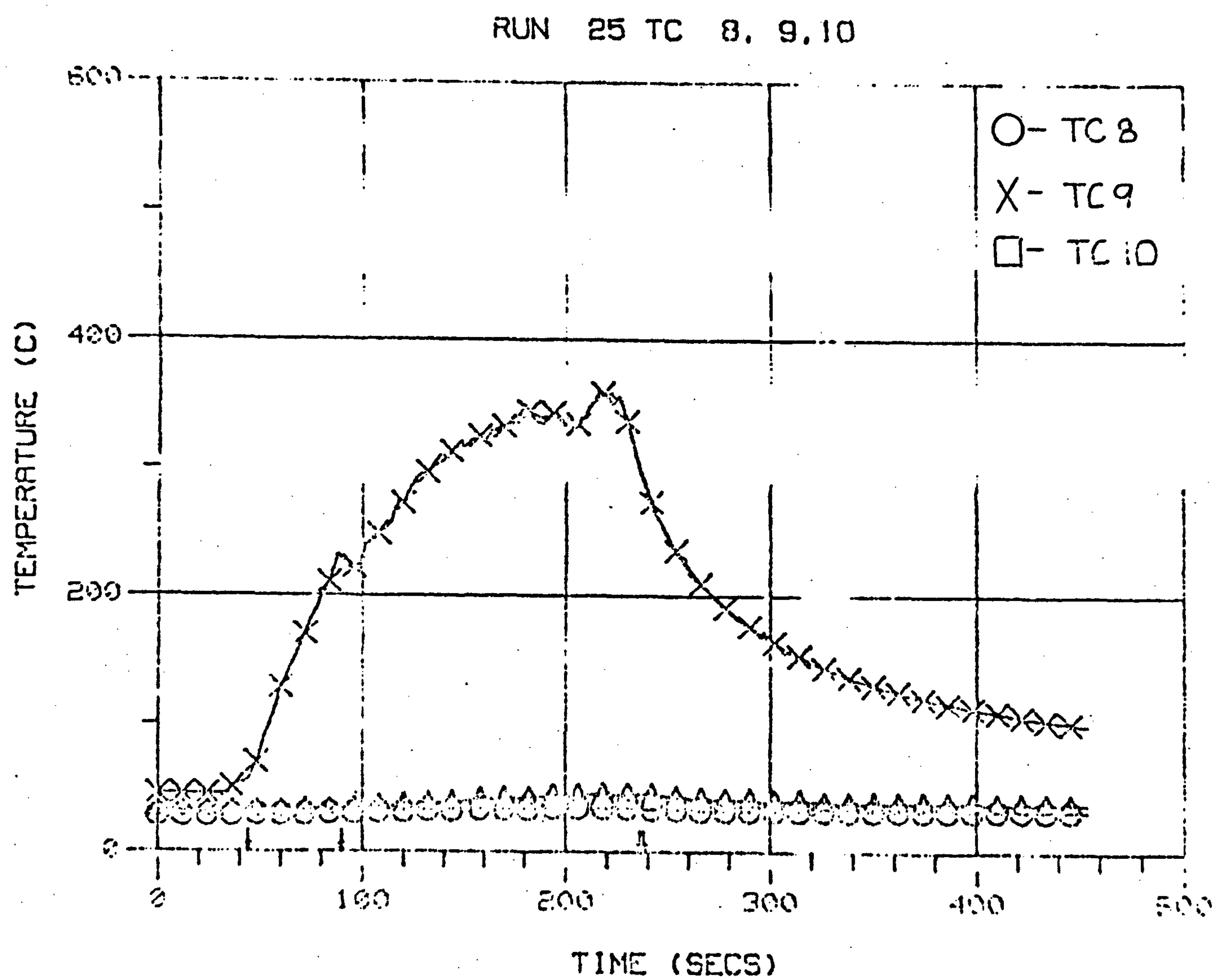
RUN 33 PRESSURES IN PV AND N2 TANKS





RUN 25 TC 1, 2, 3
○ - TC 1
X - TC 2
△ - TC 3
TEMPERATURE (C)
500
400
200
0
0
100
200
300
400
500
TIME (SECS)


RUN 25 TC 4, 5, 6, 7
O - TC 4
X - TC 5
Δ - TC 6
□ - TC 7
TEMPERATURE (C)
600
400
200
0
0
100
200
300
400
500
TIME (SECS)


RUN 25 TC 8, 9,10
600
400
200
0
TEMPERATURE (C)
0
100
200
300
400
500
TIME (SECS)
O- TC 8
X- TC 9
□- TC 10